ANALYSIS OF CASTING SUBSURFACE STRUCTURE USING ACOUSTIC MICROSCOPY

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INTRODUCTION AND LITERATURE REVIEW

This article presents the results of an investigation of the subsurface structure in 319 aluminum alloy castings using a nondestructive scanning acoustic microscopy technique. This type of analysis can reveal the grain size, constituents, oxide inclusions and porosity. This method can also be used to study various structural transformations that occur during the solidification and heat treatment processes.

Scanning acoustic microscopy uses an ultra-short ultrasonic pulse for sub-surface examination of test samples. The input signal is a single, narrow pulse while the returning signal is generally a succession of echoes. Some of the input signal is reflected back from the sample surface while the remainder propagates through the specimen until it interacts with any reflective interface. These interactions produce other echoes. These echoes reach a transducer after a time delay that depends on the ultrasound velocity in a particular area of the sample. The amplitudes of the reflected and transmitted waves are a function of the acoustic properties of the material at each scanning point. Echo reflection can be caused by different kinds of non-homogeneity or discontinuity (for example: phase and grain boundaries, voids, inclusions and cracks) [3,6,7].

The pulse method uses an adjustable time-delay gate that is used to collect individual echo-signals. All of the collected signals from a scanning area of interest, at various depths of penetration, are used to represent the C and B acoustical images [5]. Therefore, the delay gate is usually used to study reflected signals from a particular region. The pulse method requires a prior understanding of the acoustical properties of the media under investigation as well as knowledge of the necessary resolution of the interior features of interest [4,5]. The frequency of ultrasound should be selected according to the given type of sample and the purpose of the investigation. A compromise must be made between the resolving power and the degree of penetration. The depth of penetration of acoustic waves is inversely proportional to the density, acoustic velocity and attenuation in the material.

This paper demonstrates that the acoustic microscopy technique is capable of revealing porosity voids (shrinkage and gas), constituents and internal cracks on polished

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

as well as rough surfaces and in the subsurface of aluminum castings. This technique allows for visualization of the internal structure to a depth of 2.5 mm with a spatial resolution of 50 μm. It has the potential of being utilized for the on-line control of casting characteristics.

TEST SAMPLES

Casting Structure

The service properties of Al-Si-Cu castings depend on their chemical composition, liquid metal treatment and solidification rate. In general, a small, equiaxed grain structure produces optimal properties. A more homogeneous structure results in less segregation. Consequently, the casting responds better to heat treatments and defects such as porosity and intermetallic constituents are more uniformly distributed throughout the matrix. Porosity in aluminum alloy can result from excessive amounts of hydrogen (gas porosity) or a lack of feeding (shrinkage porosity) [1]. Gas porosity takes the form of rounded cavities while shrinkage porosity appears as elongated interdendritic cavities. Commercial castings can contain either type or both in combination. The service performance of automotive components, especially during high cycle fatigue, depends on the morphological characteristics of the porosity. These characteristics can be determined using traditional destructive microscopy techniques, however, these techniques are costly and time consuming. They do not allow process engineers to make proactive interventions. Consequently, it is essential that quick, non-destructive techniques for the evaluation of internal casting structure be developed that can be utilized in an industrial environment.

This experiment evaluated the ability of acoustic microscopy to characterize the internal structure of aluminum 319 alloy test samples. The average chemical composition of the test samples (as determined using optical emission spectroscopy) is given in Table 1.

Ten kg of ingots were melted in an electric resistance furnace and kept at a temperature of 730 +/- 5^{0}C for 15 minutes. Samples were taken by submerging a cylindrical graphite cup (40 mm in diameter, 50 mm deep) face down into the melt. The cup was then rotated and kept in a face up position for 20 seconds prior to being withdrawn.

EXPERIMENTAL

An ultra-short pulse reflection ultrasonic device was employed for studying the deep internal micro-structure in an aluminum casting, including porosity voids (shrinkage and gas) constituents and internal cracks. In this study, a wide-field pulse acoustic microscope with operation frequencies 25-100 MHz was used. This necessitated the use of lenses with different frequencies (25, 50, 75 and 100 MHz) and apertures (6, 8, 10 and 12). The frequency and design of each lens was based upon the analytical and numerical calculations of the propagation of focused ultrasonic pulses through aluminum casting

Table 1: Average chemical composition of the 319 Al alloy (wt%)

Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Sb	P	Na	Sr	Ca
7.554	0.394	3.452	0.238	0.326	0.008	0.009	0.122	0.052	0.0015	0.0004	0.0008	0.0009

samples. This instrument was designed by the Acoustic Microscopy Center of Russian Academy of Sciences (Moscow, Russia). Short probe pulses (3-5 oscillation periods) made it possible to resolve fine microstructural details at a depth of 2.5 mm, with a resolution of 50-150 μm.

The short probe pulses are partially reflected back to the microscope whenever a non-homogenous material is encountered. The received reflected signal is stored in a personal computer where special software recognizes, separates and processes the reflections from different internal defects and generates a visual output. This output is then analyzed and interpreted by the researcher.

A mechanical scanner is used to provide one and two-dimensional movements of the acoustic sensor for B-scan and C-scan representation of the specimen's internal structure. A scanner with scanning area of 80 x 120 mm, a maximum mean scanning velocity of 2 mm/sec and a precision of 0.05 mm was used. A computer received the collected data and provided material interface detection and recognition as well as A-scan, C-scan and B-scan imaging. It also stored the device tuning parameters for system initialization.

During experimentation, the acoustical probe assembly must contain an immersion liquid (eg. water, cooling suspension, alcohol, acetone or a special gel) to provide a continuous medium for ultrasound penetration into the object under investigation.

With respect to image processing, current methods are based on amplitude and delay time measurements of the demodulated reflected pulses. The processing of fully digitized signal waveforms permits one to increase measurement accuracy and to investigate frequency dependence of attenuation. However, special methods of digital processing are required if the return signals are greatly overlapped or transformed. This occurs when the thickness of an inclusion is about one wavelength or it is too deep to be detected using a high frequency probe. Another reason for signal distortion is the smooth change of acoustic impedance across internal structures with diffused boundaries. During experimental preparations, new algorithms for digital signal processing were developed based on non-linear parameter estimation. This method permitted us to separate pulse responses reflected from each inhomogeneity and therefore measure their time delay and amplitude [6,7].

RESULTS AND DISCUSSION

We also examined cast aluminum samples from different parts of automobile engines. Some of the samples were prepared as traditional optical microscopy objects. Others had no such ideal surface and were prepared with different surface finishes ranging from simple machined surfaces to samples suitable for optical study. A few samples were studied with the naturally rough as-cast surface.

The physical basis for the ability to locate the exact position of an object by acoustic microscope method is based on the study of the echoes of acoustic waves from an object and particles inside the object. By calculating the time delay between the received echoes of acoustic signals, the position of particles inside can be determined once the acoustic properties (e.g., the velocity at which the acoustic waves travel inside the micro-structures of inspected specimen) of tested specimen are known. One of the advantages of acoustic microscope study has been the usage of an electronic gate, which allows us to partially study a testing object. The electronic gate of the acoustic microscope allows us to scrutinize selected portions of signals over a period of time delay, and it serves as a separator, which filters out unwanted acoustic signals.

The set of figures (see Fig.1) based on aluminum sample investigations, provide an illustration of the ability to determine the flaws location by using the acoustic microscopy electronic gate method. The figures contain a collection of acoustical images showing the volume distribution of shrinkage porosity and cracks inside the sample. These consist of an acoustical image of the machined surface and four other images of the subsurface structure. The first subsurface image is based on received signals from 0.1 to 2.0 mm depths subsurface and the remaining three others with much narrower gate positions: from 0.1 to 0.5mm, from 0.5 to 1.5mm and from 1.5mm to 2.0mm). All of the pictures show high-contrast images of imperfections (the dark spots) in the bulk area of the sample. In each Fig.1.c-e both C-scans and B-scans are shown, as a cross-section along the black-color line in each of the upper micrographs. The spots show the locations of the voids and inclusions along the line.

On Fig 1a, the C-scan image shows the only machined surface information by setting the electronic gate at the surface of the examining sample. The ability to change the gate position as shown on the following schematic layout of C-scans, enables one to collect all of the returning acoustical signals received from the area inside that depth range of the input signal penetration. Fig 1 b, shows a subsurface image based on the received volume information between 0.1mm and 2.0 mm sub-surface depth by setting the adjustable time-delay electronic gate. The ability of that method lets us use the delay gate to study reflected signals from a particular chosen region or discontinuity. By re-setting the electronic gate, the volume information of Fig.1 b can be represented as a set of images with smaller volume information. Fig. 1c-e represents volume information from three different layers: between 0.1 to 0.5 mm, between 0.5 to 1.0 mm, and between 1.0 to 1.5 mm respectively. The acoustic microscope's ability to locate flaws is demonstrated by examining those images with smaller volume information. Each of the three 1c-e shows a couple of results: C-image of which the researcher chooses a particular layer and B-scan, which passed through specific cross-section (dark line) and B-scan image. Since the velocity of acoustic wave propagation is known in aluminum, by examining the time delay, the location of those flaws can be calculated (in the case of the figure 1c: they are about 0.3 mm below surface). Similar procedures on two different gate positions have been done on Fig 1 d and e. Fig. 1 d it shows that other flaws are located at about 1.0 mm below surface; Fig.1 e, - indicates that yet another flaw is located at about 1.4 mm beneath the surface. Therefore, taken together the C and B scan images provide information about the exact location of detected flaws.

CONCLUSION

This preliminary study shows the advantages of using macro-scale acoustic microscopy as compared with the light optical technique that is traditionally used to characterize aluminum casting structure. This preliminary study shows that macro-scale acoustic microscopy can characterize aluminum casting structure below the surface of a test sample, something that the light optical technique is not capable of. The results

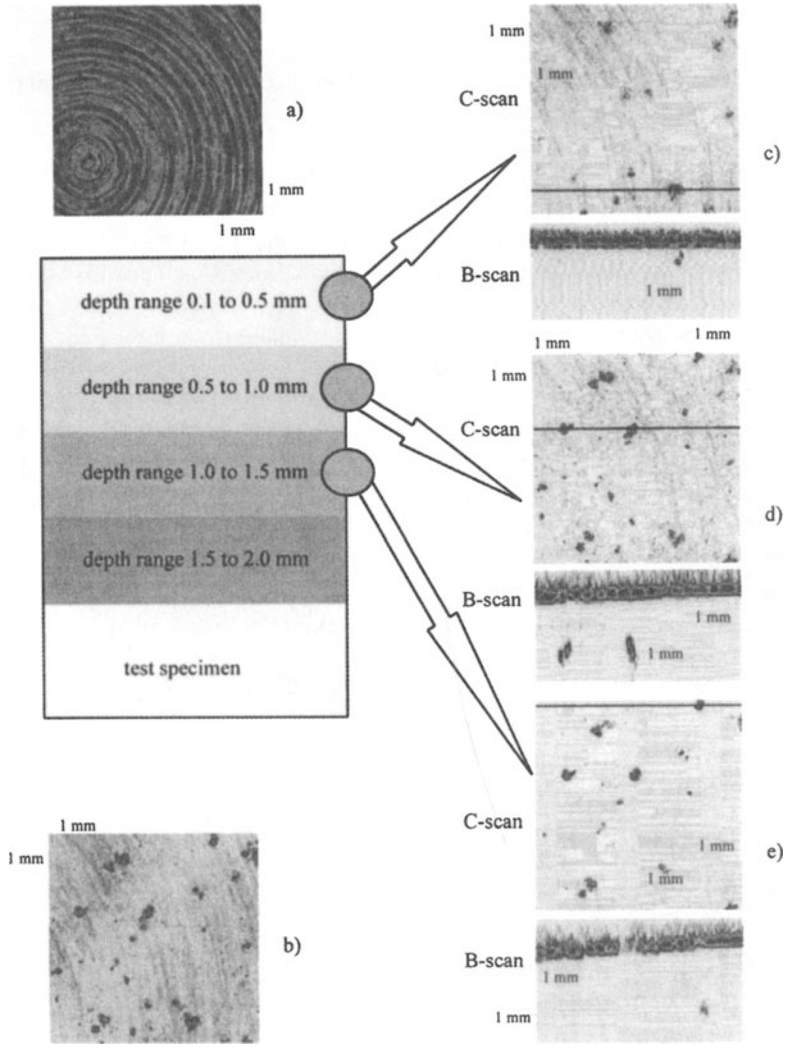

Figure 1. Acoustic B- and C-scan images for an aluminum casting sample

presented above demonstrate the ability of acoustic microscopy to recognize features in a bulk area through a relatively rough casting surface.

The main strength of the ultra short-pulse method is that it can distinguish signals from the surface of a specimen and echoes from its internal structure. The output signal of the microscope in this case is a combination of several peaks formed by different types of sound waves in the sample. By using these peaks, it is possible to identify the acoustic images of structural features such as segregation, inclusions and porosity found in the material.

The main area to which high-resolution acoustical methods may be applied is finished product inspection and detection of inclusions and discontinuities. These can include technological or manufacturing defects such as cavities (for example: conical, stratification and die), disrupted grain structures and defects caused by mechanical damage, the corrosion process and environmental damage.

ACKNOWLEDGMENT

The authors would like to acknowledge the Ford Windsor Aluminum Plant for supplying the samples used in this study.

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